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# Concept Development and Meaningful Learning Among Electrical Engineering Students Engaged in a Problem-Based Laboratory Experience

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**Abstract** This phenomenographic study documented changes in student-held electrical concepts the development of meaningful learning among students with both low and high prior knowledge within a problem-based learning (PBL) undergraduate electrical engineering course. This paper reports on four subjects: two with high prior knowledge and two with low prior knowledge. Subjects were interviewed at the beginning and end of the course to document their understanding of basic electrical concepts. During the term, they were videotaped while solving problems in lab. Concept maps were generated to represent how subjects verbally connected concepts during problem-solving. Significant to PBL research, each subject's body of meaningful learning changed with each new problem, according to how the subject idiosyncratically interpreted the activity. Prior knowledge among the four subjects was a predictor of final knowledge, but not of problem-solving success. Differences in success seemed related more to mathematical ability and habits of mind. The study concluded that, depending on context, meaningful learning and habits of mind may contribute significantly to problem-solving success. The article presents a testable model of learning in PBL for further research.

**Keywords** Electrical engineering · Undergraduate · Student concepts · Reasoning · Problem-based learning

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## Introduction

Problem-based learning (PBL) is an active learning strategy for promoting concept development and addressing alternative conceptions. Widely applied in medicine, law, and business, PBL has been shown to develop active learning strategies and hypothesis-driven reasoning abilities across content areas. PBL places students in a social learning context, fostering conceptual change as students reveal, explain, and defend their ideas within a group (Petrosino 1998; Sherin et al. 2004). However, research on contextualized learning suggests that there are always cognitive consequences, some of which may be problematic (Son and Goldstone 2009). As students apply newly-acquired knowledge, they may not apply it appropriately. For example, in studies on medical students, those students engaged in PBL developed more elaborate explanations than their peers in traditional medical courses, but their explanations tended to be more error-prone (Patel et al. 1986, 1990, 1991).

Much of cognitive research on PBL has shown that students draw on their prior knowledge when solving problems. A strong knowledge base correlates well to success in problem solving (Anderson 1987). College students working in courses outside of their majors, as well as secondary and elementary students, may be at a cognitive disadvantage when confronted with a science-based or technology-based problem because of their sparse knowledge base.

Learners of all ages possess alternative mental constructs around natural phenomena (Wandersee et al. 1994). At the college level, even students majoring in the sciences may hold alternative conceptions regarding phenomena within their field of study (for example, Ebenezer and Fraser 2001; Liu et al. 2002; Westbrook and Rogers 1996;

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Lawson et al. 1993). Students reasoning within a PBL context may rely on misconceptions and reach erroneous conclusions, thus rendering the more meaningful problem-based context less effective for learning.

## A Model of Task-Based Learning

Critical to the understanding of student knowledge construction in PBL is an examination of meaningful learning: learning that students recall and apply spontaneously to a given problem (Whitehead 1929; Bransford et al. 1993). The knowledge that students recall on a post-test and the knowledge that they actually use in problem-solving may be very different. Models based on pre-post test research designs fail to capture this important feature of learning within a PBL context: what fraction of their knowledge that students actually apply when faced with a problem. Understanding how students select from existing or newly introduced knowledge is essential for developing a complete task-based learning model. The model should guide what to include in the problem or in direct instruction, as well as what knowledge may be omitted if students can get by without it (Sherin et al. 2004). The relationship between inert and meaningful knowledge is shown in Fig. 1. The model is a visual representation of Bransford's elaborations on Whitehead's descriptions of learning during problem-solving.

The model is particularly important in understanding the differential success of students with weak or strong prior knowledge. It invites the driving question behind this study: Is success in problem-solving due to the amount of knowledge a student has at the start of the problem, as this model suggests, or is it a factor of how the student determines what knowledge is meaningful in the problem-solving context?

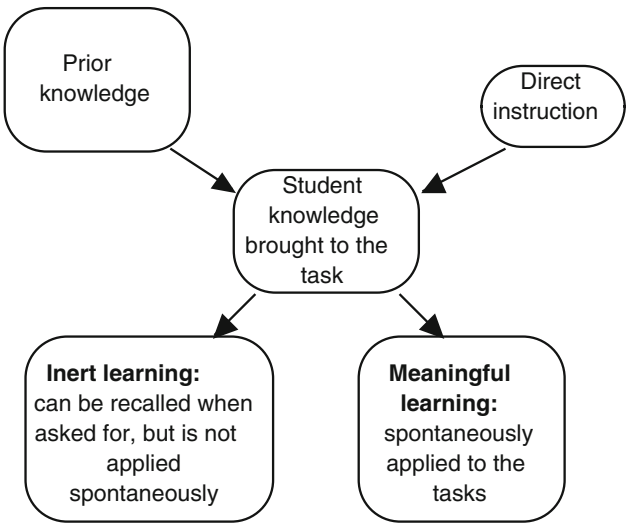



**Fig. 1** A model of learning based on Bransford et al.'s (1993) elaboration on Whitehead's (1929) model of task-based learning

The findings described in this paper are derived from a larger study on reasoning and concept development in electrical engineering students engaged in problem-based learning (Bledsoe 2007). This paper reports concept formation by selected subjects with weak and strong prior knowledge. The goals of this portion of the study were:

1. to document, analyze, and trace changes in students' concepts of current, voltage, resistance for students with low prior knowledge and students with high prior knowledge as students are engaged in a project-based engineering laboratory.
2. to observe and document the development of meaningful learning and changes in the body of meaningful learning throughout an electrical engineering course.

## Theoretical Framework

Student understanding of electrical phenomena was examined within a phenomenological perspective in order to best describe (1) the students' experiences of electrical phenomena and (2) the relationship between each student and the content knowledge across time. In this study, phenomenology is defined using Lincoln's (1990) description of phenomenology as an inquiry paradigm, where both researcher and respondent are co-participants in the inquiry process. In addition, Moustakas' (1994) view of phenomenology as a research method framework and Roths's (2005) studies using cognitive phenomenology shaped the perspectives of data collection and analysis. Moustakas' framework is grounded in Husserl's (1913) work on transcendental phenomenology, which focused on intentionality, the orientation of the learner's mind toward the object. The researcher's role is to set aside biases and prejudices or at least to recognize them at the outset, then describe the subject matter as much as possible on its own terms. This position, termed *epoché*, strives for a description of the phenomenon as seen by the respondent, clear of the researcher's own perspectives of "correct" or "incorrect" conceptions.

Phenomenography as a research method grew from the phenomenological framework. Phenomenography attempts to capture the learner's perceptions of natural phenomena, and the variations in perspectives within a group of learners (Liu et al. 2002). Within this perspective, student conceptions are viewed not as fixed mental models, but as a fluid relationship between the learner and the subject (Marton and Booth 1997). Out of a study of a group of learners, the researcher attempts to sort student conceptions into mutually-exclusive descriptive categories, often hierarchical, that may later drive curriculum development (Ebenezer and

Fraser 2001). Within this study, student perspectives on electrical phenomena were analyzed through phenomenographic methods to develop categories of knowledge, which provides a framework to examine changes in student knowledge over time.

## Methods

The students in this study were engaged in a first-year electrical engineering course at a state research university on the west coast of the United States. The course was taught during winter quarter. During the fall quarter, students had been introduced to the school of engineering, learned some basic electrical concepts, learned to solder circuits, and constructed a small circuit board. During the winter term, students reviewed the concepts of current, voltage, and resistance in greater detail, then applied these concepts to complex problems in class. The term concluded with an introduction to digital logic. The researcher did not participate in instruction.

The lab portion of the course employed a hands-on robotics "platform for learning" called TekBots™ (Oregon State University 2007). Students purchased the kit at the beginning of the term, and used it throughout the term in solving both structured and open-ended problems. Labs met once a week for the 10 weeks of the term. A maximum of 24 students attended each lab. The lab sections were supervised by two or more graduate teaching assistants. For most assignments, students could work alone if they chose, but most students elected to work with other students at their workbenches. Each lab assignment took 2 weeks to complete. The first assignment was highly structured, consisting of the instructions for assembling the TekBots™. Subsequent assignments used the robotic platform to address problems in circuitry. The first problems were short, structured problems that were usually solved within the lab period. Later problems were more open-ended and required time out of class to solve. By the end of the term, the students were to successfully solve an open-ended engineering problem in which they were to make their wheeled robot into a "bump bot" that would, on encountering an obstacle, back up and change direction. As an extra credit problem, students could add photoreceptors to their TekBots™ and create a robot that would follow a flashlight beam.

### Subject Selection

The subjects were purposefully selected from first-year engineering students enrolled in the winter quarter course. On the first day of the class, a two-tier survey developed by the researcher was administered to the entire class as a sorting tool. The pretest consisted of seven questions on DC circuits derived from Mazur (1997), McDermott and van Zee (1985), and Shipstone (1984). The first question asked students to draw a simple circuit made up of a battery, a bulb, and one or more wires. The next six questions showed a circuit and asked students to make predictions about the behavior of the circuit. Students were given a choice of answers to circle, then asked to provide a written explanation of their answers. For sorting purposes, the surveys were initially scored for the number of correct answers circled. Written responses were later analyzed along with interview data to develop a description of student conceptual understanding. The entire survey appears in Bledsoe (2007). A sample question is shown in Fig. 2.

From a pool of students who volunteered for the remainder of the study, twelve were selected: those scoring in the lowest quartile and the highest quartile of the range of class scores. The purpose of this deliberate selection was to identify students entering the course with high prior knowledge and low prior knowledge compared with the larger body of students. Out of this pool, seven students completed the study.

Two subjects with high prior knowledge and two with low prior knowledge are described in detail in this paper. These students were selected for description as exemplars of high and low problem-solving success within their prior knowledge class. The implications of an apparent disconnect between prior knowledge and problem-solving will be discussed.

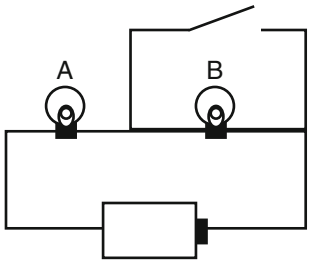
### Data Collection

All subjects were interviewed within the first 2 weeks of the term. During the interview, subjects were shown their initial survey and asked if they still agreed with the predictions they had made, and were asked to explain their ideas. They were then given a board with batteries in holders, bulbs in sockets, and a bundle of wires with alligator clips at the ends and were asked to construct each of the circuits in the survey. They were then asked to explain what they observed. The interviews were videotaped for later analysis.

The interviews were carried out as a dialogue between researcher and subject. The subjects were assured that it was their conceptions that were important rather than reaching the "right" answer. The interviewer's role was to listen attentively, and ask questions only to further clarify views, as described in Ebenezer and Fraser (2001). Rather than asking, "What is voltage?" which tends to elicit a recital of textbook definitions, questions began with phrases such as, "How do you explain…" in order to uncover the subjects' own ideas. This helped elicit if–then propositions from subjects, such as, "If the current is flowing in

**Fig. 2** Sample question from the conceptual survey administered at the start and at the end of the course

**4. Observe the circuit below, which includes a dry cell, two bulbs, and a switch:**




Circle as many of the following that will happen when the switch is closed, and explain in the space below:

A will get brighter  A will get dimmer or go out  B will get brighter  B will get dimmer or go out

this direction, then what we should see is this bulb lighting up first."

Researcher observations on students engaged in lab tasks captured evidence of concept use and conceptual change. Students were videotaped at work, and the tapes were later transcribed for analysis. The researcher engaged subjects in conversation from time to time to elicit their ideas about the purpose of the lab, to capture student–student talk during the labs, and to capture explanations of what they observed as they completed the lab exercises. Each subject was observed a minimum of three times during lab.

Course lectures were also observed. Packets of class notes, made available on the class website, were collected for analysis to identify the instructor's target concepts, and to determine if students used the target concepts, examples, and model circuits as they addressed the problems in lab.

At the end of the term, the survey was administered to the class again. The seven subjects were interviewed regarding their post-survey answers using the same interview methods as the initial survey.

## Analytical Method

Transcriptions of video records, observation notes, and responses on the survey forms for each of the seven subjects were analyzed to infer categories of knowledge held by the subjects. Rather than categorizing statements as "scientific" or "alternative," analysis attempted to capture the subjects' viewpoints using the phenomenographic methodology described in Ebenezer and Fraser (2001). The phenomenographic method holds that a natural phenomena is conceptualized in a finite number of ways and can be described as mutually exclusive categories (Marton and Booth 1997; Ebenezer and Fraser 2001). For example, in this study, subjects were interviewed to uncover their concepts of current, voltage, and resistance. Two of seven subjects interviewed stated they could not describe what voltage was in the initial interview. The remaining subjects in the initial interview and all subjects in the final interview expressed some concept of voltage, and their concepts fell into one of four hierarchical categories. While the beliefs of individual subjects did not necessarily move stepwise through all categories in the hierarchy, the hierarchical order emerged from the overall direction of conceptual change across all subjects, from naïve (no concept of voltage) to the target concept as taught in lecture. Lowest on the hierarchy was the belief that voltage and current were similar in nature, expressed in statements that described voltage as moving or flowing. Instruction during lecture explicitly contradicted that belief, yet some students continued to equate voltage and current with a second belief, in which they described voltage as a measure of current. A third belief, also following instruction and reflecting models involving pool balls moving through a tube, was an expression of voltage as pressure or "push." At the top of the hierarchy of beliefs about voltage was the belief that voltage was a form of potential energy. This was the target concept taught in lecture. Students using this belief discussed voltage as a causative factor in creating current.

Transcripts were coded using TAMS Analyzer 3.3 qualitative data analysis software (Weinstein 2005). Initially, the data were coded to categorize student statements regarding the concepts of energy, electricity, current, voltage, and resistance. After the categories were established from multiple passes through the data, and student statements were sorted, the researcher consulted prior literature on student concepts in electricity to compare the boundaries of phenomenological categories obtained in the current study with earlier descriptions of student concepts with, most notably Shipstone (1984, 1985), Osborne and Freyberg (1985), and Osborne (1981). Triangulation with prior research showed that the categories uncovered in this

study around the concepts of energy, electricity, current, and voltage aligned well to descriptions of electrical concepts found in prior studies. A full description of this portion of the analysis and the conceptual categories can be found in Bledsoe (2007).

Analysis then tracked the responses of individual subjects to concentrate on following the changes in their conceptions and the interplay between material learned in lecture and material actually used in lab to uncover what emerged as meaningful learning during problem-based instruction. Subject statements from each interview and from the observations were used to construct concept maps to document the relationships between concepts that the subjects expressed during each observation. The concepts expressed in the first interviews represented a body of knowledge that each subject carried into the lab experience. Concept maps of the lab observations were more challenging to construct. Asking subjects to think aloud during lab proved too intrusive. Conversations with subjects after they had successfully solved a problem did reveal approaches to reasoning, as did conversations between subjects and their bench partners and with the teaching assistants. Of particular interest was capturing the knowledge that subjects spontaneously applied during lab without coaching from the teaching assistants. The researcher assumed that this knowledge held the most meaning for subjects.

After the concept maps were constructed, the videos were again reviewed to test the consistency of the maps. Copies of the graded lab exercises were collected from each subject and their responses compared with the concept maps as another test of consistency. Where possible, subjects were asked to comment on representations of their prior concepts, though member check was not possible on the final concept maps, as analysis and concept map construction continued after the study was over.

## Results

Description of results will focus on four of the subjects, two who entered the course with low prior knowledge (AM and MJ) and two who entered with high prior knowledge (JF and TA). While much of the literature about prior knowledge and problem-based learning suggests that subjects with low prior knowledge would achieve less over the course of the term than those with high prior knowledge, results were more complex than expected. These four subjects exemplify the range of results obtained. A full description of the results for all subjects can be found in the original study (Bledsoe 2007).

Subject AM (low prior knowledge) was male, age 19. He had studied electricity in a college-level physics course and had built his own computer, giving him some prior practical experience with electrical circuits. He was enrolled in the first year of a 2-year calculus sequence. AM scored 6 out of 24 on the initial survey.

Subject MJ (low prior knowledge) was female, age 23. MJ recalled no prior courses where she had learned electrical concepts, and due to advising errors, had not taken the fall introductory electrical engineering course. She believed she had an aptitude for math and had been advised to consider engineering as a career. She was enrolled in the second year of a 2-year calculus sequence. MJ scored 8 out of 24 on the initial survey.

Subject JF (high prior knowledge) was male, age 24. JF could recall no prior coursework that included electrical concepts, but he had worked in construction where he had learned about wiring, and had wired lights in his own home, giving him practical experience with electrical circuits. He was enrolled in an introductory algebra course. JF scored 15 out of 24 on the initial survey.

Subject TA (high prior knowledge) was male, age 29. TA had taken electronics courses in the US Navy about 10 years prior to the study, and described himself as an electronics hobbyist. He was enrolled in the second year of a 2-year calculus sequence. TA scored 23 out of 24 on the initial survey.

### Comparing Initial and Final Interviews

All four students showed changes in knowledge during the course of the term, as might be expected from instruction and practice with these concepts, though not all students achieved the target concepts as defined by the professor in the written instructional documents for the course. Concept maps based on student statements were used to diagram the ways in which concepts interrelated at the start and at the end of the term.

### Subject AM

In his initial interview, AM described current as "electron flow," describing it in material terms as particles (electrons) moving through wires. Current was something that could be "used up" by bulbs and other circuit elements. His material view is evident in statements about a light bulb lighting: The bulb lights by a process of "electrons moving through, coming out of the positive end, going in through there, uh, sparking with whatever element's in there, and coming back through." In clarifying what happens in the bulb AM stated, "The power's mixing with whatever's inside, um, the, the chemical that's inside it." He also expressed a belief that a battery was where electrons were stored and emerged "from the positive end."

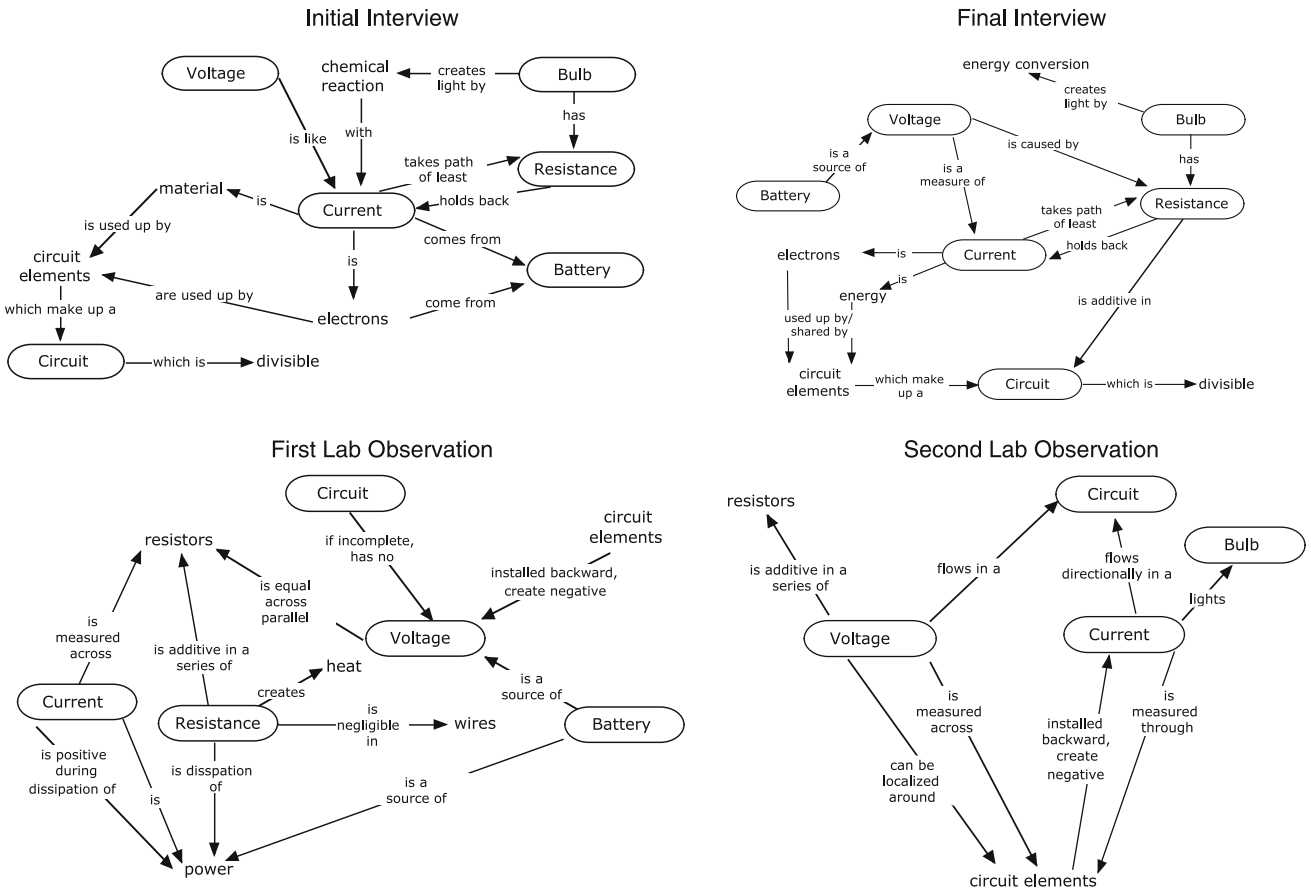



**Fig. 3** Concept maps created from AM's interviews and lab observations. While current remained a central concept in both interviews, AM's understanding of voltage and resistance increased in complexity

As can be seen in the concept map in Fig. 3, current figured largely in AM's discussion of circuits, and other concepts were discussed in their relation to current. When questioned about what he was measuring when he measured voltage, AM first guessed that it might be "the number of electrons at a given moment." When asked to clarify, he thought for a moment and stated, "Hmm… the current would be the flow of electrons and R, resistance, is how many electrons are being held back, er, not how many, it's just, just a number. I mean 4.7 ohms, it's not going to hold back 4.7 electrons. So yeah, I guess it makes sense that voltage would be the number of electrons."

A concept map of the final interview, also shown in Fig. 3, shows that current was still the primary concept that AM used to discuss electrical phenomena. AM's explanation regarding light bulbs later changed to an energy conversion theory in the final interview, where he described electricity converting into heat and light. However, in the final interview, AM maintained an essentially material view when he described resistance as something that holds back the flow of electrons, and interpreted voltage as something to do with current: "I'm going to say it's the change of, um, like electrons flowing. Not flowing. Just the like either the drop or the increase between one point and the other." Contained in this is an idea of potential differences, which also was contained in his new view of batteries as a source of voltage rather than current. Current itself he expressed as both "energy" and electron flow, and his predictions regarding the outcomes of parallel and series circuits revealed that he expected current to be "used up" by circuit elements. AM's post-survey score was 15 out of 24.

## Subject MJ

MJ's interview took place after she had been to several lectures. She demonstrated tentative conceptions around current, voltage, and resistance. A concept map of her ideas (Fig. 4) shows that like AM, she focused on current in her explanations and less on voltage. She described current explicitly as a form of energy and as electron flow, and she believed that current could be used up by bulbs and other circuit elements. She did not state the source of current in a circuit. The battery, she believed, was a source of voltage,

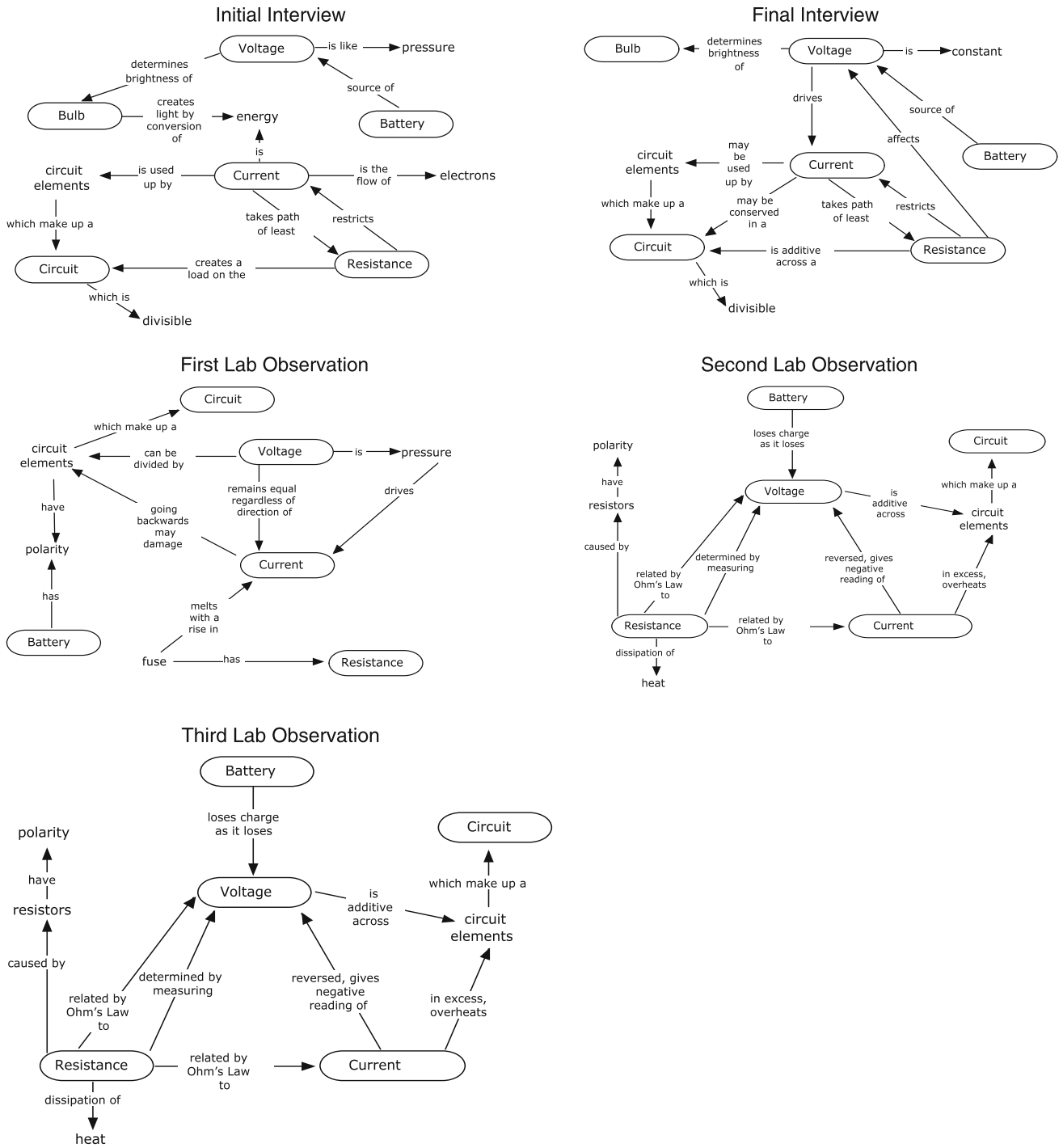



**Fig. 4** Concept maps created from MJ's interviews and lab observations. While MJ's initial understanding was low and the connections between concepts were few, the overall framework of her knowledge remained similar from the beginning of the term to the end, while new connections were added between concepts

as voltage was printed on the battery, and she believed that voltage affected the brightness of bulbs in series, stating, "…it seems like the voltage would be determining the brightness of it, and it seems like if, the only way they would not be the same brightness if there were something in the light bulb regulating it to say, you know, you're giving me too much voltage." This statement suggest an idea that voltage flows like current, but MJ also described voltage as being "like pressure." MJ also used the term "load" in her descriptions of circuit phenomena to describe what was happening around resistors and bulbs. She had initially thought that the first of two bulbs in series should

be as bright as a single bulb in its own circuit. She was surprised to see that both bulbs in series dimmed equally, and in trying to explain the discrepancy, she stated, "It's because it has a bigger load on it? And it's drawing more?"

MJ's final interview, also shown in Fig. 4, demonstrates an integrated understanding of both voltage and current. Interestingly, MJ's concept of current became slightly more material, as she did not describe current as energy but instead described current being "used up" by circuit elements. At the same time she recognized that current was "conserved" in the circuit, and she struggled to reconcile a view of current as something both "used up" and "conserved" as well as the idea that current flows one direction while the actual electrons flow in an opposite direction, a concept that had been taught in lecture. Voltage she understood as a force that drives current, and its source was the battery on the circuit board. While MJ was dissatisfied with her explanations about current and voltage, she was adept at using Ohm's Law and similar mathematical formulas used in class to discuss the relationships between current, voltage, and resistance. This result is similar to other work on college student understanding that contrasts conceptual understanding with mathematical modeling of physical phenomena (Melendy 2008). When she employed Ohm's Law in trying to explain circuit phenomena, MJ was better satisfied with her explanation. For example, when asked to describe the dimming of a bulb placed between two resistors regardless of which resistor was changed, MJ explained:

> It's changing the current, because the current through all three of them has to be the same because they're all in series, but the current, let's see — since V=IR, if you increase the resistance, then the current has to go down. And if you decrease the resistance, the current has to go up. So we increased the resistance and the current went down, so now there's a dimmer light bulb.

While MJ's conceptual understanding of current and voltage were not strong enough to satisfy herself, an understanding of mathematical relationships helped her successfully predict and explain circuit behaviors. MJ's post-survey score was 15 out of 24.

### Subject JF

JF initially expressed a high degree of confidence in his understanding of circuits based on his prior experiences. Having once wired a set of overhead lights in series, he had discovered for himself that this would not give him the brightness that he wanted. Like others in the study, JF's conversation in the first interview focused largely on his concepts of current, and he openly acknowledged that he did not understand what voltage was though he was familiar with the term.

JF's understanding of current was strongly material. On his initial survey, he expressed the belief that when a bulb was placed between two resistors, if the resistance on the side where the current came from was increased, the bulb's brightness would decrease, but if the resistance on the other side were increased, then the bulb should increase in brightness. While he had changed his mind by the time of the second interview, he explained that on the survey he had thought of current like a river and a resistor like a dam. If current accumulates behind the second resistor, the bulb should get more current:

> If you — if this is dammed up, if you dam up before the light bulb it's going to get less, if you dam after it's going to get more water.

In the interview, JF rejected this idea based on instruction in lecture and predicted that the resistor should have the same effect regardless of which side of the bulb it was located. He also described bulbs themselves as resistors in a circuit and noted that the circuit in the problem that had a bulb between two resistors actually had three resistors in the circuit.

JF's only expressed understanding of voltage was based on hearing the term "voltage divider" in lecture. He noted that bulbs wired in parallel split the voltage between them. Implicit in this was the idea of voltage being something that flowed like current. Figure 5 shows a concept map of JF's views in the initial interview.

In the final interview, JF talked equally about current and voltage, and discussed resistance in relation to both. He described voltage as something like pressure that drives the flow of current. Batteries, he knew, registered a certain amount of voltage across the terminals and the voltage in the battery pushed current through the circuit. He struggled, however, to explain why a resistor that reduced current should register higher voltage across the two ends. His view of current retained a material character, as he discussed the highly directional nature of its flow through a circuit and described resistors as objects that impeded the flow of current. An acceptance of voltage as something like pressure allowed JF to understand the function of the battery, but his belief that voltage was pressure that moved current failed to help him explain voltage as a potential difference across the ends of the resistor.

The knowledge that JF expressed confidently was based on his direct experience, both prior to and during the lab itself. He had no doubts that bulbs wired in series would be dimmer than bulbs wired in parallel, as he had wired both types of circuits in lab and in his own home. However, when it came to explaining why, JF was at a loss:

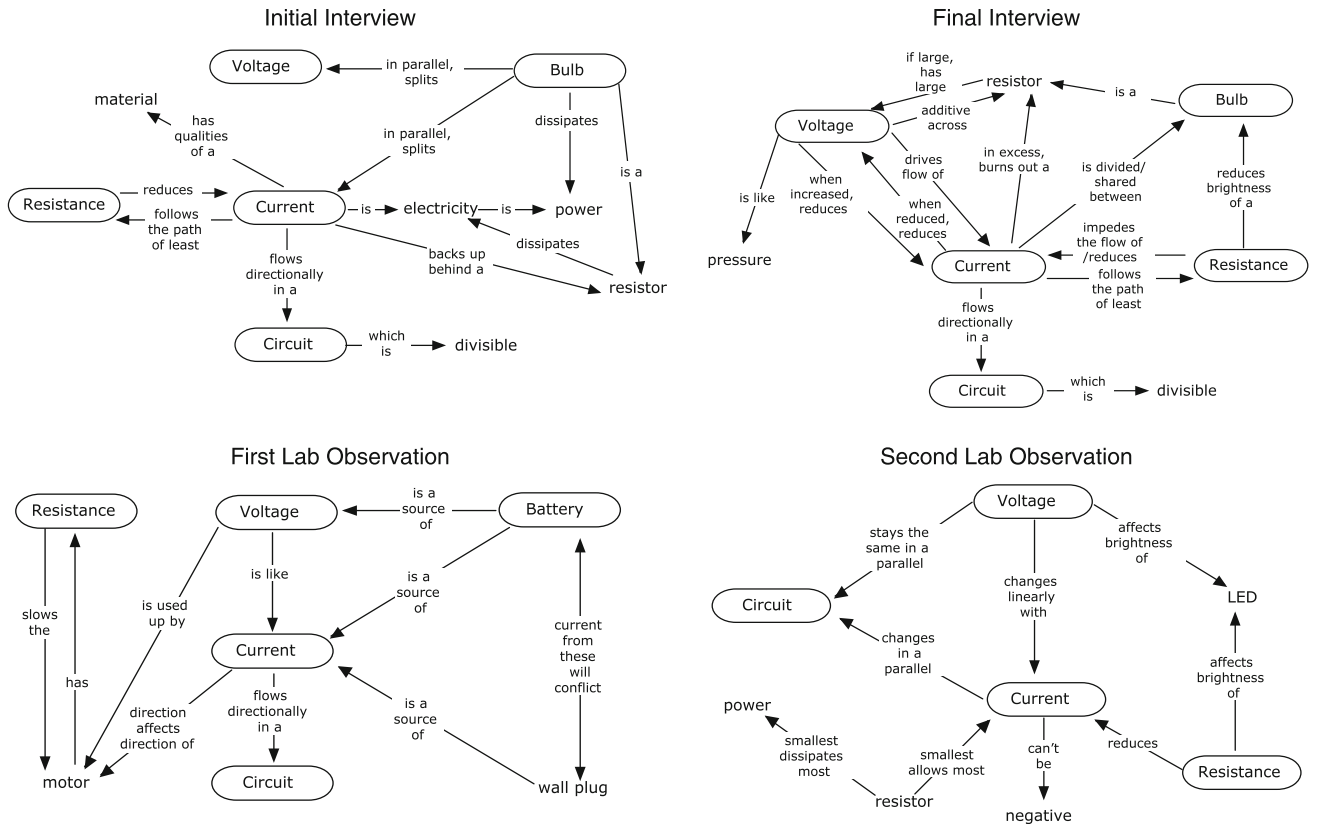



**Fig. 5** Concept maps created from JF's interviews and observations. JF showed a great deal of practical knowledge of circuitry in both interviews, showing an increased ability to make connections between concepts by the end of the term

> This has got something to do with a term that I don't remember. Um. Voltage divider. I think. Something to do with that. I don't know. It's just — I just know it. I don't know why, that's the problem.

## Subject TA

Out of all of the subjects, only TA included as much talk about voltage and resistance as he did about current in the initial interview (see Fig. 6). Like MJ, he struggled to understand what voltage was:

> Well, I guess voltage is, it's kind of potential energy. It's always measured at a reference. But I guess I don't have a really clear concept of, okay this — wait, voltage is supposed to be, like if you compare it with water, like a hose, the pressure.

However he could describe what voltage did, generally in mathematical terms. In comparing two bulbs in series to a single bulb connected to a battery, TA explained:

> We're going to have, like this is what? (pointing to battery) three volts total on the circuit here. So each [bulb] is going to have, the change in voltage is going to be one and a half volts across each one. Um, I guess it's because the voltage drop is equal and the way they're made up, the resistance should be about equal. Um, all that's saying is the current's going to be the same, which I already said.

TA described current as the flow of electrons through wires. Interestingly, in his interview he did not explicitly connect the idea of voltage as "pressure" with the idea of voltage as the force "pushing" electrons through the wires, though this concept came out later during lab observations. TA also described resistance as something that restricts the flow of electrons.

In the final interview, TA explicitly connected voltage, resistance, and current. He stated that in a circuit, where resistance was 0, voltage was also 0. If voltage was 0, then current should also be 0. TA's responses during the interview were highly focused on the problem, revealing only a small part of the knowledge that he had expressed during lab on the same concepts. His written responses on the final survey, however, revealed knowledge that was not expressed in the interview. In general, TA seemed to express more through written words than spoken.

In both interviews, TA tended to view each circuit as a mathematical problem to be solved and talked more about mathematical relationships than about what he believed

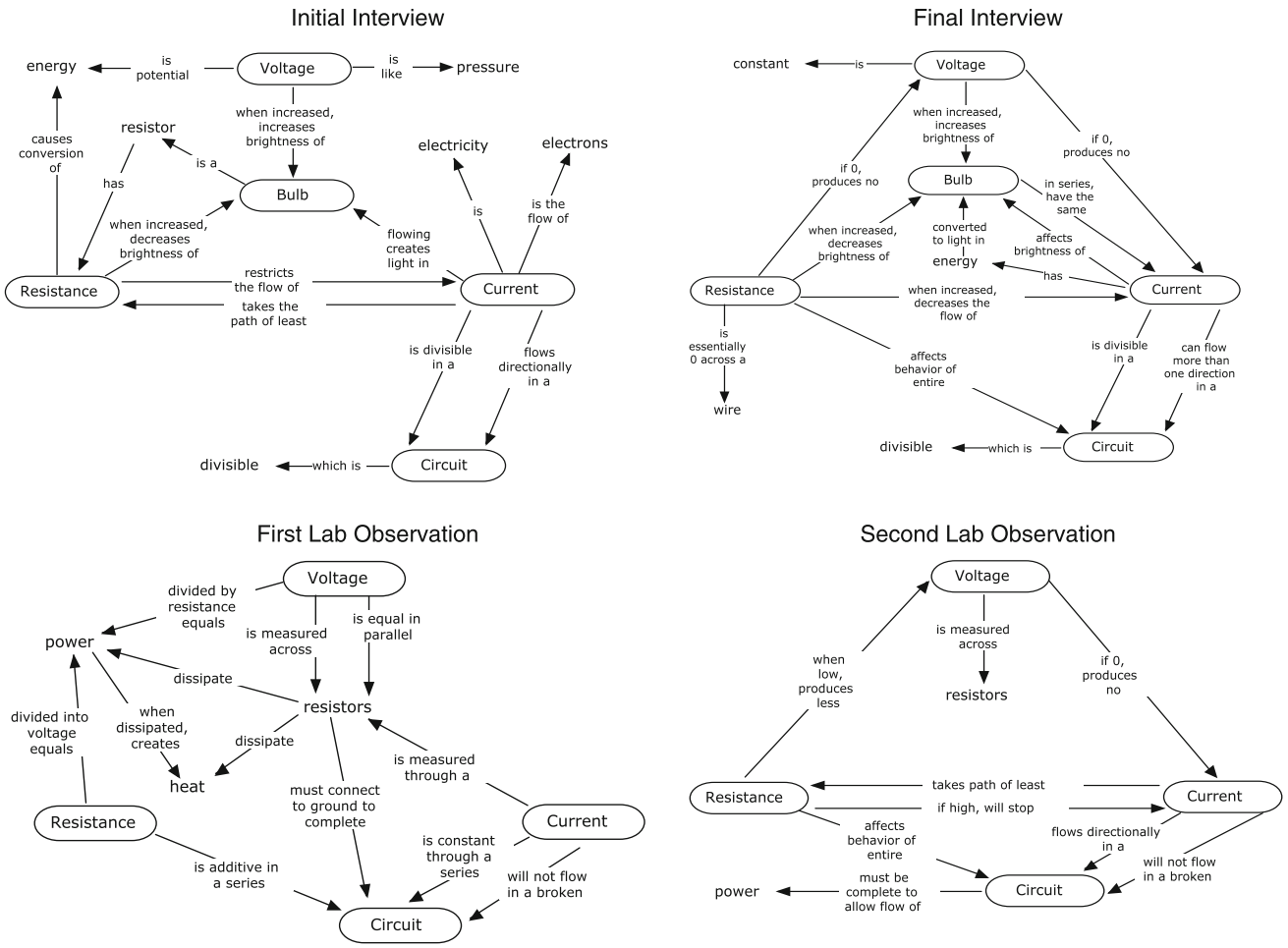



**Fig. 6** Concept maps created from TA's interviews and lab observations. TA showed extensive conceptual knowledge in both interviews, as well as multiple connections between concepts

voltage, resistance, and current were in terms of physics. In his response to the problem of comparing two bulbs wired in parallel to a single bulb, his written response in the second survey employed a more explicit use of Ohm's Law:

> Given that the bulbs are made identically, they will have equal internal resistance. Given voltage V, and resistance R, the current through A will be V/R. The current through D will be V/R also.

TA described the same problem during the final interview in similar terms:

> Now that they're in parallel, um, you've got, well it's like two isolated circuits here. You've got one like — the voltage is the same across both of these, so you've got the full, your source voltage. The resistance in each of these loops is just the one, the light bulb's internal resistance, so it's identical to this, so V equals I times R and it's the same as this one, it's the same current.

TA was adept at developing explanations using the relationships between resistance, voltage, and current, recognizing the interrelatedness of all three concepts. TA's post-survey score was 24 out of 24.

## Making Knowledge Meaningful: Solving Lab Problems

One would expect conceptual change over a 10-week course. Pertinent to the questions of this study, however, is how students use their prior knowledge and the knowledge they gained from instruction as they approach problems. The Whitehead-Bransford model (Fig. 1) suggests that the body of meaningful learning—the learning that students use spontaneously as they problem-solve—increases as students increase their knowledge base and increase their experience with problem-solving. In this study, concept maps assembled from student comments during lab, actions taken during lab, written homework responses, and later discussions during interviews describe a body of knowledge that students found meaningful solving problems in

lab. Separate concept maps were constructed for separate events in order to determine what knowledge emerged as meaningful during each event.

The lab tasks were complex, requiring that students remember and apply multiple abstract concepts as well as appropriate procedural knowledge and apply them simultaneously and accurately to the problem at hand. The cognitive load was at times overwhelming. Working in pairs or teams was encouraged, and many students combined their understanding with fellow students to solve the problems. Subjects were as likely to encounter trouble by misremembering procedural knowledge, such as wiring a multimeter to measure voltage versus current, as they were by attempting to apply their alternative conceptions to the lab tasks. The knowledge that students brought with them had a direct effect on their performance, but prior knowledge of electrical concepts was not the only influential factor.

## Students with Low Prior Knowledge: AM and MJ

AM and MJ entered the course with low prior knowledge of basic electrical concepts and little experience with electronics. The expectation based on prior research (Anderson 1987) was that with a smaller knowledge base to draw upon, they would have more difficulty solving problems than students with high prior knowledge. However, differences in habits of mind between these two subjects produced very different outcomes. While AM did struggle with concepts as expected, MJ's more intense study practices and methodical approach led to higher success in problem-solving and greater conceptual change than AM. During problem solving, AM tended to rely on procedural knowledge where he could apply the procedures used in a prior exercise or a sample circuit in lecture to solve the problem before him. When this strategy failed, AM relied on the skills of neighboring students or on trial and error. By contrast, MJ tended to ponder the problem first, alone or in discussion with a neighboring student, and attempt to apply conceptual knowledge in order to predict how a given circuit would behave before she assembled it. If her predictions were not supported, she turned to the teaching assistant or another student and again sought to understand the problem conceptually.

The first observation of AM took place within days of the initial interview, when the class was working on a set of theoretical exercises involving protoboards and a variety of circuit elements, including resistors, motors, and diodes, to understand how they functioned. All of these circuit elements would be used as students designed and assembled their "bump bots" later in the term. The activities that AM worked on in the first observation were highly structured so as to develop necessary procedural skills and conceptual understanding. During the observation, AM and a lab partner wired resistors in parallel and series, then measured voltage across and current through the resistors and noted the dissipation of heat energy from the resistors.

A concept map based on AM's talk and actions during the activity (Fig. 4) shows a focus more on procedural knowledge and practical applications of concepts than on the concepts themselves, and reveals changes in his understanding since the initial interview (Fig. 4). AM had altered his concept of batteries to include them as a source of "power" (a term he used interchangeably with "current") and as a voltage source. In the course of conversations about why there was no voltage reading on a circuit they had built, AM said to his partner that the circuit might be incomplete, suggesting a belief that voltage is present only in complete circuits where current is flowing. This is a consistent application of his belief in the initial interview that voltage is something similar to current. Reinforcing this was the discovery that it was important to install certain circuit elements in the right direction, or the partners would obtain a negative reading for voltage. AM also discovered that installing a diode backwards caused it to heat to the point of smoking, further reinforcing the idea that the term "polarity" referred to the direction in which elements were meant to be installed in reference to conventional current flow.

When measuring voltage across and current through resistors in series and in parallel, AM predicted, based on knowledge obtained from lecture, that one large resistor should dissipate as much heat as several small resistors in series, and easily solved the lab problems involving additivity of resistance in a series circuit. However, while AM was able to measure voltage across a resistor, he then tried to measure current in the same fashion—that is, connecting the terminals of the meter across the resister while set on a current scale—risking a blown fuse. A teaching assistant told him that the multimeter must be wired in series into the circuit and intervened to help AM wire the circuit correctly. While AM stated the knowledge in the initial interview that current takes the path of least resistance, even after instruction from the teaching assistant he had difficulty applying this knowledge to the correct use of a multimeter. The instrument measured current when its probes were placed across a resistor creating a short in the circuit; that is, creating a path of least resistance. AM appeared to view the multimeter as a measuring tool that was separate from the circuit and therefore not involved in the circuit's functions. While AM did not express this explicitly, other subjects in the study and other surrounding students expressed surprise on first learning that the multimeter became part of the circuit when in use.

A second observation took place 3 weeks later. AM and his partner were working separately on a 2-week exercise

in which they were to apply prior lessons on digital logic to create a control board for the motor of their robot. If successful, students should have a board that would cause the robot to move forward and backwards. When moving forward, a green indicator LED should turn on. If moving backward, a red indicator LED should light up. Students had model schematics to work from that suggested part of the solution, and were guided by written instructions through some preliminary exercises to measure voltage across transistors and other elements in the circuit.

By this observation, AM's activity demonstrated his use of acquired knowledge that voltage is measured across circuit elements while current is measured through them. Voltage he viewed as something that flows like current, but with localized aspects, as he asked the teaching assistant how to measure voltage "through" a transistor. The teaching assistant indicated where to place the multimeter probes, on one side of a transistor and the ground. AM asked, "But wouldn't that just go through everything? I just want to find the voltage around this."

AM made the LEDs on the board light up, pointing out the success of a completed circuit to his partner indicating with gestures the flow of current through the board that caused the LEDs to light. When it came time to measure current, AM allowed his partner to do the measurements, stating that his partner was more skilled. Reliance on the skills of others was a frequent strategy that AM employed when he was unsure of his own success. The two worked together to take and record readings from the multimeter. Polarity of the transistors was important in the conversation as the two decided if the transistors were installed correctly. AM stated at one point, "You need to switch 'em," to which his partner replied that the results would be the same. AM responded, "Not too sure about that. They might be a negative. Because, you know, direction will be changing." In this, AM was referring to the direction that the robot would be moving, stating the purpose of the exercise as, "We're probably going to have to put like switches on here so we can turn it left or right. That'd be my guess." AM also commented on how voltage of resistors "adds up" in a circuit.

During this observation, AM also made the comment that he was having difficulty understanding the lessons in lecture on digital logic, stating that they "went right over my head." He tended to ascribe his failure to understand entirely to the difficulty of the subject matter, and did not appear to be changing his learning strategies to increase his understanding. Yet in addition to understanding and applying basic electrical concepts, students needed some elementary understanding of digital logic to be able to use diodes and bipolar junction transistors as digital switches to make the robot carry out its function as a "bump bot."

In the final interview, AM described his limited success with his "bump bot." The motor ran and the wheels turned, but it did not successfully negotiate a maze as he thought it should. AM's approach was largely trial-and-error. AM used schematics from the lab to construct the basic plan for the bump bot. When it came to constructing the circuitry to make it respond as desired when bumping into an object, AM did not have an effective strategy nor sufficient grasp of digital logic to design and construct circuits on his own.

During the final interview and several times during observations, AM expressed a general frustration with the course. He was aware that his understanding of electrical concepts was incomplete, and ascribed his lack of success on the final project to his lack of understanding of digital logic. He stated that given a schematic he could assemble the parts, but found it difficult to understand the "theoretical parts," saying, "In lab I could make sense of where everything was supposed to go and I could trace where everything was flowing from and to on a board or what not, I was able to set up the protoboards just fine, but what was actually going on—." He described the practical hands-on construction of circuits and the conceptual understanding of their function as "pretty much two different worlds" which he had been unable to reconcile. While he recognized his conceptual shortcomings, at no time did he discuss any study strategies. Observations and artifacts showed that he attended lab and did the required homework, but did not attempt any optional problems nor did he attend any optional workshops that were offered. AM ascribed his lack of understanding to external causes: the difficulty of the class, and his feeling that the instructor was not teaching well enough for him to understand.

MJ also came into the class with low prior knowledge of electrical concepts, but both her learning strategies and her outcomes were somewhat different from that of AM. MJ's first observation took place the same day as the interview and her activities at that time consisted mostly of finishing the assembly of the robotic platform. The second observation took place as MJ and a partner were working on the same activities that AM had worked on in his first observation, including measuring voltage and current in a circuit that included an electric motor, and working with resistors in series and parallel. Most of the talk between the partners focused on procedures, measurements, and calculations. During this observation, MJ made references to Ohm's Law, which had been learned in lecture, and made sense of several of her observations by relating them to Ohm's Law. At one point, MJ and her partner (also a subject in the larger study) had measured internal ammeter resistance, motor current, and voltage across a 1 ohm resistor in the circuit, and now had to fill in a blank labeled "Calculated motor current using 1 ohm resistor."

| | |
|---|---|
| Partner | Got to figure out why we need the resistance of the voltmeter. That we figure was 9.2 ohm resistor. So. (thinks) So resistors in series—do you add them all—1 over 9.2 |
| MJ | Wait, why are you adding all those together? |
| Partner | Adding the resistance up |
| MJ | Okay |
| Partner | Because the voltage across them is the same |
| MJ | So, are you trying to come up with the number that goes here? [indicating a blank on the lab worksheet] |
| Partner | Um, yeah |
| MJ | Just do V equals IR and get voltage which equals I times R, the resistance |

In building circuits for the exercises, MJ carefully observed the resistors to make sure they were installed in the right direction, concerned with the polarity of parts. In the course of the activity she and her partner discovered that resistors gave off heat, and by touching the resistors they had physical evidence of the energy conversion. Talk between the partners was around data gathering as they measured voltage and current, and about calculating the dissipated power. MJ indicated that she knew that too much current through a circuit element could cause the element to overheat, recalling warnings in lecture about "smoking" the resistors in the circuits. As they worked, MJ used the multimeter to directly measure the resistance of resistors she was using. She also used the colored bands to determine the resistance, curious to see if the resistance she measured was the same as the resistance that was indicated by the color coding. On discovering that she obtained a 1.4 ohm resistance on a 1 ohm resistor, she asked the teaching assistant why that would be, and they engaged in a conversation about the resistance of the wires in the meter, the meter itself, and the precision of the resistors as sources of error. This kind of curiosity that led her beyond simply following lab instructions was characteristic of MJ in all observations. To satisfy her curiosity, MJ relied on her own observations, as well as knowledge she obtained by asking the teaching assistant and other students for their ideas.

Like AM, MJ's talk was more situational than theoretical. She talked less about what voltage and current were than what they were doing at the moment. Her understanding of the relationship between voltage, current, and resistance was expressed mathematically using Ohm's Law, which she used successfully to find answers to the questions posed in the lab. Nevertheless, expectations created by her underlying conceptual understanding influenced her actions during lab. For example, her idea that current flowed directionally influenced her to check the direction in which she installed resistors in the circuits.

At the third observation (Fig. 4), MJ's concepts around voltage had increased. As in the prior observation, she demonstrated expectations that voltage should drive current, and that if she got a negative reading for voltage, she should get a negative reading for current as well. The expectation, however, led MJ and her partner into an error during one of the activities. The first section of the lab had students compare two types of semiconductors: diodes and bipolar junction transistors. MJ expressed the purpose of the first part of the activity as: "We're trying to see, let's see, we're trying to find out, show the nature of the diode. So that we can know what a diode does and how it works." MJ and her partner wired a circuit that included an LED and a potentiometer, which acted as an adjustable resistor. This allowed them to change the resistance in the circuit without removing and replacing resistors. They were to wire an ammeter into the circuit and use another multimeter to measure voltage across the LED. What students had to discover was that the LED acted as a switch. When MJ and her partner wired the circuit, the LED did not light, a significant event that they failed to notice. As they measured voltage and current, MJ showed increasing uneasiness that something wasn't right, but her numbers showed a linear relationship between voltage and current that her prior understanding predicted. In fact they should have found that current remained at 0 until voltage was high enough, at which point current should have increased exponentially. The linear relationship satisfied MJ, and she went on to the next activity until one of the teaching assistants saw the graph and asked them to re-do the circuit. On doing so, they discovered that the LED was defective, and may have been wired into the protoboard incorrectly. MJ's understanding of polarity and directionality of current came up in the conversation:

> Still, it wouldn't make sense that we had both negative and positive — even if it were backwards. I can see it could be wrong— Um, let's see. Is it backwards, though, because I was going by the polarity on the voltage, er, voltmeter, so that might be backwards. Is it? (checks diagram in book) Okay, here – because the current is flowing that direction. And the current flows from positive to negative – right?

Once the circuit was wired correctly and the LED lit, MJ and her partner took measurements again. Once again, MJ's expectation that current and voltage are linearly related drove her expectations of the outcome. At one point, MJ asked her partner, "Do you have any voltage?" Her partner indicated that he did. MJ asked, "Well, then how come I have zero current?" The teaching assistant, who was watching, indicated the potentiometer and noted that it was turned to the highest resistance, "so you're losing the whole voltage." MJ responded, "It makes sense

then that it has zero current," drawing this time on her understanding of the relationship between current and resistance that she extracted from Ohm's Law. From there, MJ was able to predict the switch-like nature of the diode and predicted that the outcome for the graph would be exponential, not linear.

To explain their first results, MJ drew on her knowledge of shorted circuits, hypothesizing that the first circuit that they had built must have had a short in it somewhere. Later in lab she applied this concept to other circuits, checking each one carefully for potential shorts that could bypass critical circuit elements.

MJ showed a tenacity in her work that worked in her favor as she struggled to understand concepts and complete lab activities. Several times during observations she mentioned taking a circuit home and working on it outside of lab if she wasn't satisfied with the results or if she had not understood a concept in lab. This was in contrast to AM who completed only the required exercises in class, left early if he finished the minimum required work, and did not work on problems outside of class. MJ also formed a habit of drawing circuit schematics and using the schematics to predict outcomes before building circuits, in contrast to AM's strategy of finding similar model circuits in lecture or lab notes and building those in a trial-and-error fashion. MJ applied both of these habits to the bump bot problem. While a fourth observation of MJ in lab as she worked on the bump bot yielded very little talk about her concepts, she did talk about her problem-solving approaches and she demonstrated both of these strategies as she worked on building the robot. When she wasn't sure of the outcome of a schematic, she stated that she would try it out and see what happened, so her problem-solving strategy involved both informed predictions and trial-and-error. Particularly troubling to her was an optional challenge problem of making the bump bot into a "photovore," a robot that would follow light. While she understood the basic nature of the photoreceptors, she struggled with developing a precise understanding of their response to specific light intensities as well as a way to incorporate them into the circuit.

After discussing the problem at length with one of the teaching assistants, MJ sat down with her schematic again and worked out a series of equations as she traced the predicted actions in the circuit. After some time she concluded that she needed to test parts of the circuit in a more trial-and-error fashion to see how they would behave and use the outcome to inform her logic.

In the end MJ was successful at building a functioning bump bot. Her schematic for the front bumper produced a working circuit that resulted in the behavior desired. However, she did not get the optional "photovore" to behave quite as she had hoped for. While it detected light, it did not consistently follow a light beam.

At the final interview, MJ expressed a positive attitude toward further studies in electrical engineering. Throughout the term she attributed her knowledge gains to the extra work she had put in, including taking circuits home to work on, doing lab exercises over again, and sometimes working optional problems. When discussing concepts where she felt she lacked understanding, she tended to ascribe this to internal causes: that she needed to work harder on understanding a particular concept.

The final survey suggested that both AM and MJ achieved similar gains in content knowledge around the basic concepts of current, voltage, and resistance. AM scored 6 on the initial survey and 15 on the final survey out of a possible 24. MJ scored 8 on the initial and 16 on the final survey. Content knowledge gains therefore may not account for the difference in problem-solving success and meaningful learning between these two students.

### Students with High Prior Knowledge: JF and TA

Two subjects, JF and TA, entered the course with high prior knowledge and high prior experience with electrical systems. The expectation based on prior research (Anderson 1987) was that these two subjects would demonstrate higher problem-solving ability in the lab, as they had greater knowledge to draw upon. However, as with AM and MJ, these two subjects experienced different levels of success in lab, suggesting that other factors than content knowledge influenced their outcomes.

JF described himself as a "hands-on" learner. His preference was to apply a trial-and-error approach based on his prior experience. For JF, experience and observation preceded concept formation. While this led him to understand the target concept by the end of an exercise, it often led him astray at the beginning. Insufficient conceptual knowledge or incorrect application of conceptual knowledge frequently led JF to choose inappropriate procedures. TA, by contrast, used conceptual strategies similar to MJ's. He generally read the problem and studied the diagrams or schematics first until he could understand the problem in terms of mathematical relationship. Once conceptualized, TA then selected strategies from his procedural knowledge, relying only on trial-and-error to "tweak" a completed circuit until it performed to his satisfaction.

While JF's knowledge measured at the high end of the survey scale (15 out of 24), JF stated that his ability to predict the outcomes of simple circuits came more from his physical experience with wiring and circuitry during building construction than from an understanding of the underlying phenomena. However, in spite of his performance on the initial survey and in the initial interview, JF came into the lab with several prior conceptions that

influenced his thinking about the concepts of voltage, current, and resistance.

The first observation of JF took place during a lab in which students were carrying out introductory activities on the relationships between current, voltage, and resistance. Their first problem was to discover which of several methods was the most accurate means of measuring current. JF, after looking over the schematics, concluded that the activity was about measuring voltage to the motor wired into the circuit with and without resistance, and expected the motor to slow down when a resistor was added. The resistor, however, was equal to the internal resistance in the ammeter. Like AM, JF did not recognize that the ammeter became a part of the circuit when in use, and saw it as something quite separate. His alternate view of the activity's purpose left him puzzled when he was asked to calculate the motor current using Ohm's Law and the voltage from the batteries, until his lab partner coached him:

| | |
|---|---|
| JF | But I don't know what the motor current is |
| Partner | Motor current? Well, you know the voltage. You know the resistance. You're good to go |
| JF | I don't know the voltage, though |
| Partner | You don't? |
| JF | That right there? [pointing to meter] That's my batteries. That's just— |
| Partner | No, it looks like it. Yeah, it's the voltage from the batteries |

Once coached, JF recognized the activity as an Ohm's Law problem and successfully carried out the calculations. However, in the next activity, JF expressed a new concept of voltage that led to another point of confusion. In this problem, students had to wire their robotic platform, using suggestions from a schematic, with a switch that in one position would allow the wall plug to charge the batteries, and in another position would let the batteries discharge to run the motor. In both cases the wheels of the robot would turn. JF, on discussing the problem with his partner and the teaching assistant, believed that voltage from either the battery or wall plug would be used up by the motor and would drop when the motor ran. He also applied a highly material view of current when he expressed the idea that the circuit could not work because current from the wall plug and current from the battery would collide, like two streams of water. Here, the teaching assistant stated that differences in voltage would determine which direction current would flow: that the wall plug had a higher voltage, and that current would flow from the higher to the lower voltage. JF was satisfied and proceeded with the exercise.

In a second observation, JF was working on the same diode problem that gave MJ difficulties. Like MJ, JF initially expected that as the potentiometer was turned, the current should increase linearly with the voltage. His partner, referring to instruction from lecture, noted that the transistor in the circuit acted as a switch, allowing no current through until the voltage reached a given level. JF then observed the circuit again and noting the LED, predicted that changes in resistance and voltage produced by turning the potentiometer should change the brightness of the LED. Here, JF drew on prior knowledge of how incandescent bulbs behaved, expecting the LED to behave in the same manner. His partner reminded him that the LED was a diode that was either on or off and did not change in brightness. To test this idea, JF spent several minutes turning the potentiometer and observing the LED until he was satisfied that this was true and that he understood why. This was consistently JF's preferred mode of learning, which he demonstrated and expressed verbally on many occasions: hands-on activity, observing the results, then forming a concept.

JF's highly hands-on, try-it-and-see approach to the lab activities resembled AM's strategy. Like AM, JF was dissatisfied at the end of the term with his understanding and his progress. His knowledge of basic electrical concepts had increased (with a score on the final survey of 24 out of 24), but his "bump bot" had not succeeded. JF expressed concerns that his level of mathematics achievement had interfered with his ability to understand the digital logic and programming necessary to make the robot operate. Where other students in the study were in their first or second year of calculus, JF was enrolled in college algebra. While no calculus was used in the course, JF felt that his lower level of mathematical understanding interfered with his ability to solve problems, particularly problems in digital logic. He stated that he was re-thinking his major, and intended to take more mathematics before moving on in the engineering program.

TA entered the program with a past history of practical knowledge of circuitry from his Naval training. His score on the pretest was near the ceiling (23 out of 24). While he struggled to recall vocabulary during the initial interview, his understanding of the mathematical relationships between voltage, current, and resistance were sufficient to make accurate predictions regarding the circuits on the initial survey and during the interview.

During his first observation, TA worked quietly and alone to assemble his robotic platform, which yielded too little science talk to construct a useful concept map. However, at the second observation, TA worked with a neighbor who needed help with the activities, which yielded considerable conversation about the activities and the underlying concepts.

TA's talk reflected both his grasp of the lab exercises and his underlying concepts. During an activity that involved measuring power dissipation in resistors, TA

measured voltage and current in order to calculate power dissipated, then used the results obtained to frame his understanding of the circuits in his explanations to his partner. For example, TA and his partner ran current through a single large resistor and found that resistor became very hot, then arranged several resistors in series that equaled the total resistance of the large resistor. Even before applying current to the circuit, TA predicted, "…this was the overloaded resistor. I bet by using the same amount of resistance but spreading it over five resistors, that the power dissipated by each one will be within the range." TA and his partner then applied current and discussed the results, noting that the dissipation of power produces heat, and that the voltage should be equal across resistors wired in parallel, which TA remembered from lecture. He also made multiple references to the relationships in Ohm's Law as he explained how to determine power dissipated in the circuit.

TA's statements also included the practical aspects of assembling circuitry. He reminded his partner several times that voltage must be measured across resistors while current is measured through. He noted that if the circuit wasn't completed by connecting the resistors to the ground on the protoboard that current would not flow, stating, "If you don't complete to ground, you're going to have an open circuit." While a linear model of circuits was rare among the responses on the initial survey, it was not uncommon for students in lab to have initial difficulty in creating a complete circuit on the protoboard without some assistance.

In the next observation which occurred 2 weeks later, TA and his partner had completed the required lab problems and were engaged in an optional challenge project to create an audio amplifier. As in the prior observation, TA's partner had difficulty creating complete circuits, prompting TA to remind his partner that the circuit must connect to the ground in order for current to flow. The circuit they were attempting to build included digital logic gates that controlled whether current reached the motor or not. TA noted that the high resistance in the circuit through the motor controller effectively cut off current. He reminded his partner of concepts they had discussed in the prior observation: that where voltage measured 0, there would be no current, and that voltage must be measured across a resistor. He also stated that any resistor in the circuit would affect the entire circuit, not just those components "downstream" of the resistor, and that current takes the path of least resistance.

By the end of the term, TA had successfully completed his "bump bot" project, creating a robot that would successfully negotiate a maze. He also completed optional challenge problems in addition to the required lab activities.

Both TA and JF began the term with prior experience, and with high prior knowledge, though TA had greater prior knowledge than JF. At the end of the term both TA and JF showed similar understanding of current, voltage, and resistance, and were able to successfully solve the circuitry problems on the survey. Yet while TA was satisfied with his progress and performance, JF ended the term dissatisfied and questioning his career path. A number of factors contributed to the different outcomes between these two subjects. JF believed his mathematical ability was not up to the level he needed to succeed in the course, while TA was in second year calculus. This difference could, as JF believed, have contributed to their differing success with digital logic.

Habits of mind demonstrated during lab also differed between the two subjects. When working with a partner, TA took a mentoring role and guided his partner during the exercises. JF, on the other hand, received guidance and mentoring from another partner, and relied heavily on concrete examples from lecture as models when trying to create circuitry to carry out a particular function.

Meaningful learning also appears to have been a factor. TA seemed more facile at applying his understanding of Ohm's law and basic electrical concepts to lab problems and the final bump bot problem, while JF struggled to understand the intent of many problems. JF's preferred mode of learning—hands-on experience leading to conceptual understanding—did not align well with the expectation that he create his own problem-solving procedures based on conceptual knowledge. While both subjects had adequate conceptual knowledge, their meaningful knowledge—that body of knowledge that each subject recognized as relevant to a problem—differed considerably.

## Discussion

The results of analysis indicate that there were different kinds of knowledge in use during problem solving. The detailed examination of initial knowledge, experiential background, and approaches to problem solving revealed that high academic understanding was valuable for performance on the bump bots problems. However, higher knowledge also came in the form of procedural knowledge gained through experience that was not as easily translated into problem solutions. Similarly lower initial knowledge supported early success, when coupled with productive habits of mind, such as seeking abstractions or generalizations, resulted in successful problem solving. This discussion will outline a synthesis of knowledge use in problem-based learning that suggests students with lower initial knowledge going into a problem-based setting can apply and build on that knowledge through strategic support in relevant reasoning skills. These skills include approaching a problem systematically, reflectively examining one's

own sense of the overall purpose for solving the problem, and looking for generalizations and abstractions leading to knowledge transfer.

It was clear by the end of the 10-week term that all four students' conceptual knowledge had changed, as most moved toward the target concepts presented in lecture. More pertinent to the study, however, was how subjects were using their knowledge when working on solving problems in lab, and how the lab activity in turn contributed to conceptual change. The body of meaningful knowledge each subject demonstrated while working was derived from knowledge obtained from lecture and from prior labs, interacting at times with prior conceptions and with each other. What is significant is that while the total body of acquired knowledge grew and changed, the meaningful learning—that is to say, the learning applied directly to each problem—was highly contextual, changing not just with a subject's entire body of knowledge but also with the problems themselves, or more accurately, what each student thought each problem was all about.

The primary question driving the study was: Is success in problem-solving due to the amount of knowledge a student has at the start of the problem, or is it a factor of how the student uses the knowledge and how the student determines what knowledge is meaningful in the problem-solving context? "Knowledge" takes on multiple shades of meaning in this context. Facts and examples that subjects could remember from lecture were not always recalled and applied where appropriate to laboratory problems. Whitehead's (1929) categories of "inert" and "meaningful" knowledge become critical in understanding the relationship between conceptual knowledge and problem solving.

A comparison of conceptual change and of problem-solving success in students with high prior knowledge and low prior knowledge shows that students in both groups experienced conceptual change as a result of both direct instruction and the lab experience. A simple comparison of pre- and post-survey raw scores suggests that the students who entered with high prior knowledge had an advantage over those with low prior knowledge in terms of conceptual understanding. AM scored 6 (out of a possible 24) on the pre-survey and 15 on the post-survey, while MJ scored 8 on the pre-survey and 16 on the post-survey. Their post-survey scores were similar to JF's pre-survey score of 15 and lower than TA's pre-survey score of 23. Both JF and TA scored 24 on the post-survey.

However, looking at actual performance in the lab suggests that the knowledge needed to predict the outcomes of simple circuits on the surveys was only one aspect of the knowledge, skills, and habits necessary to success in the problem-based lab, particularly on the final bump bot problem. Furthermore, the survey outcomes did not distinguish between problem-solving approaches that later influenced success in problem-solving in the lab.

The nature of meaningful knowledge of electrical concepts that subjects applied to problem-solving also differed. JF's hands-on, try-it-and-see style derived from a knowledge that consisted of previous practice and recalled outcomes from past experience. He applied that knowledge to the pre-survey, recalling, for example, a series circuit that he had once wired that had resulted in bulbs that were dimmer than desired. In lab as well, the knowledge that JF applied consisted of examples recalled from his prior background, lecture, and prior labs. From his construction experience, JF derived what Cook and Brown (1999) referred to as "knowing." In contrast with "knowledge" about actions, knowing is action or an aspect of action. JF was able to successfully perform certain actions meaningfully, but was not readily able to connect that "knowing" to explicit statements about electric circuits. While JF's hands-on approach helped him form concepts in lab, as when he adjusted the potentiometer and observed the behavior of the LED, he did not appear to abstract the knowledge into an overall explanatory model. Each new problem he appeared to treat as unique, and it took some coaching from teaching assistants or other students before JF recognized a series of small problems as all relating to a particular concept. JF's ability to successfully perform certain procedures, his "knowing", cannot be directly translated into explicit knowledge. According to Cook and Brown (1999), this will require a dynamic interaction with the learning opportunities of this situation.

TA's knowledge, on the other hand, was expressed from the beginning of the course in terms of relational models such as Ohm's Law, which he operationalized and applied to various problems on the surveys and in labs. TA was able to successfully predict the outcomes of circuits on the survey by taking a model-based approach, applying what he knew of Ohm's Law to each of the problems, and taking into account the interactions between voltage, current, and resistance to predict outcomes. TA appeared to view the individual problems on the survey as examples of a single, unifying set of principles described in Ohm's Law. Throughout the lab activities, TA continued to refer to Ohm's Law and other relational models learned in lecture as he approached lab activities and the final bump bot problem.

The two students with low prior knowledge demonstrated a similar dichotomy. AM demonstrated a trial-and-error learning approach somewhat similar to JF's, but lacked a similar knowledge base at the start of the term. There was less purpose to his actions, less of what Dewey (1938) called "productive inquiry". JF had the knowledge and an overall sense of purpose that brought otherwise

haphazard activity into organized information linked to current knowledge. JF's failure to solve the "bump bot" problem was something he attributed to his lack of knowledge of mathematics and logic required to carry out the programming rather than a lack of knowledge of basic electrical concepts. In contrast, AM had more mathematical background, but had difficulty making predictions regarding the circuits on the initial survey because of low prior knowledge regarding the behavior of electrical circuits. As AM's knowledge increased over the term, his ability to predict the outcomes of circuits increased, leading to increased success on the same problems on the post-survey. AM's predictions were based on prior observations and examples: he had observed the difference between circuits wired in series and those wired in parallel during the lab activities, and applied the prior observations to the tasks on the survey. MJ, who also scored low on the initial survey, also had a low knowledge base to draw upon when making predictions. However, from the start of the course, MJ tended to rely on abstracted relational models such as Ohm's Law to solve problems and was able to use these relationships between voltage, current, and resistance to reason her way through problems. In addition, MJ employed several habits of mind with success. Like TA and JF, she displayed "productive inquiry," with a distinct sense of purpose. She showed a willingness early on to attempt optional problems, and when puzzled, displayed a tenacity that drove her to seek answers through continued study on her own or to consult with other students or the teaching assistant. MJ also had higher mathematical knowledge than JF, enrolled as she was in second-year calculus at the time of the study. Using digital logic in the "bump bot" problem was less of an issue for her than it was for JF.

## Conclusions

As the model in Fig. 1 suggests, the students in this study demonstrated a difference between meaningful and inert learning. To each problem they applied only that portion of their knowledge that they believed was applicable, according to their interpretation of the task. However, contrary to what the model suggests, the body of meaningful learning among these four subjects did not necessarily increase with each task, but rather changed with each task as the subject drew from a larger body of knowledge only those facts, examples, or models that the student deemed appropriate in the context of the specific task. Which knowledge was activated appeared to be influenced by a subject's interpretation of the task at the outset. During the task, knowledge that was contained in the body of previously inert learning could be activated if the student's idea of the purpose of the task changed, or if the subject struggled with an unexpected outcome, as when JF believed one lab was about measuring voltage to the motor with and without a resistor, when the activity was about applying Ohm's law to determine the most accurate way to measure current. Coaching from the TA and a fellow student was required before JF was able to alter his views of the task and then reselect the knowledge that he believed was meaningful in that problem-solving context.

Besides academic knowledge, subjects brought other kinds of knowledge to the complex problem space that influenced the outcome of the task and further learning. Within these four students appeared two very different problem-solving approaches. AM (low prior knowledge) and JF (high prior knowledge) appeared to look at each task as distinct and unconnected, and attempted to solve the problems by recalling examples of similar problems. Their problem-solving success rate tended to be low compared with the other two subjects, and they tended to rely on the teaching assistants and fellow students for guidance. TA (high prior knowledge) and MJ (low prior knowledge) tended to view the problems as examples of a larger concept or model, and applied that concept or model to solving the problems. Their problem-solving success rate was higher, and while MJ and her partners tended to rely equally on one another, TA took a mentoring role toward the student he partnered with.

The results cannot be explained by prior knowledge of electrical concepts alone. Other factors appeared to influence the outcomes, one of which was habits of mind. Mathematical achievement may have been a contributing factor; JF at least perceived his lower mathematical ability as a barrier to success. Self-efficacy (i.e. one's sense of what can be done with the knowledge in hand) was not considered in this study; however, given that some subjects took a mentoring role while others were habitually recipients of mentoring suggests that self-efficacy is a factor worth examining in the future.

Figure 7 is a proposed model, outlined originally in Bledsoe (2007), to capture the complexities of learning in a problem-based context. In this model, meaningful use of knowledge is both an input into a complex problem space, and a product that is applied to other, similar problems. Inert knowledge may be activated and becomes meaningful during the task. Likewise, portions of the body of knowledge that emerge from the problem space may be inert in the context of successive problems, but may be activated during that task.

While not a topic of the study, some anecdotal evidence suggested that habits of mind may play a role in problem solving. MJ's tenacity in attempting to solve problems, which included reconstructing lab problems at home to further her understanding of the outcomes, was a strategy

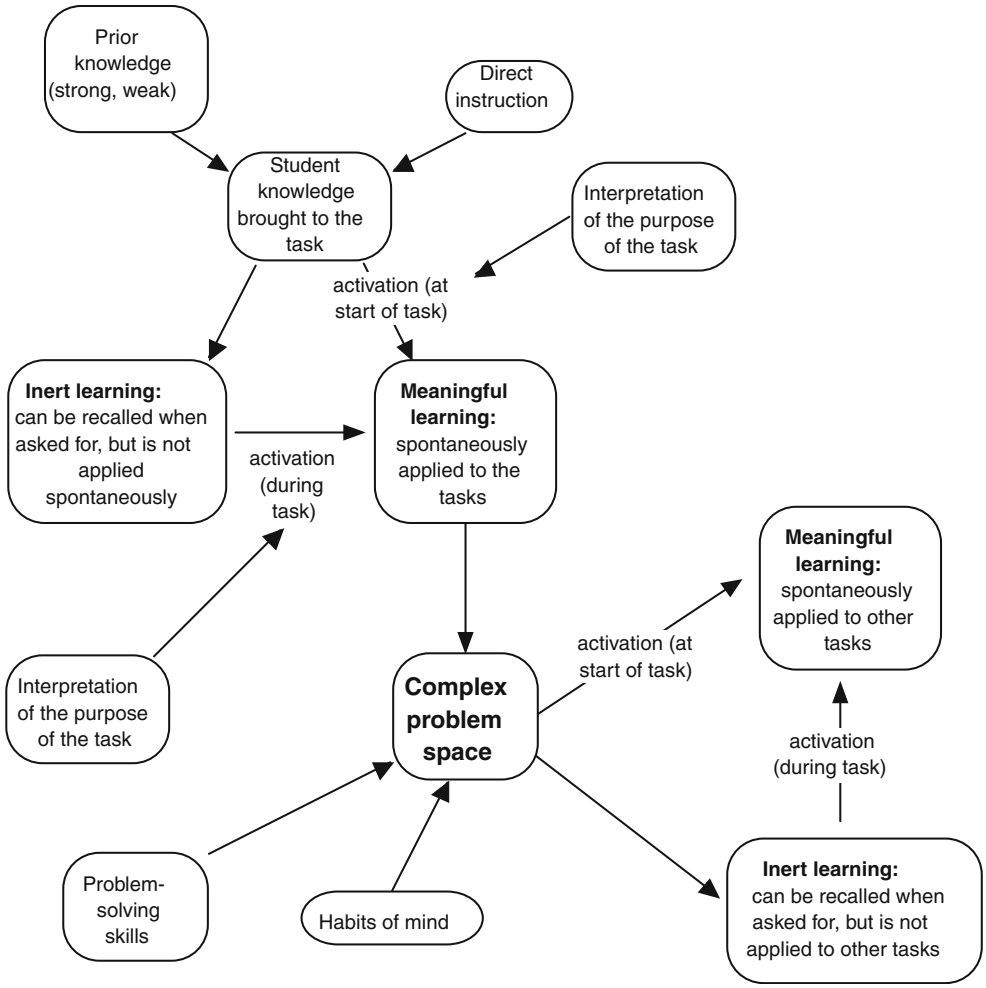



**Fig. 7** Proposed model of learning in PBL

that was instrumental in solving the final bump bot problem. AM, who did only the work that was required, did not engage in reflection, review, and practice as did MJ, did not succeed at the bump bot task. Hence, habits of mind are suggested here as part of the model, but this is a feature in need of further research.

This model suggests that student learning is only one factor that influences success in PBL, and is not necessarily the most predictive of problem-solving success. A deeper understanding of the factors that students bring to the complex problem space—their problem-solving approaches, the lenses through which they interpret the purpose of the task, and their habits of mind—can further inform and improve PBL instruction.

To further inform and refine the model, more work will be needed to understand the factors that appeared to influence subjects in this study including: how student interpretation of a problem-solving task influences the final product and the content learned; how tacit conceptions of how to solve problems influence student performance in a PBL context; and finally whether a student's role in a mentor–mentee student partnership influences—or is influenced by—a student's problem-solving ability.

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